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# Characterizaiton of Particulate Emissions from Municipal Wastewater Sludge Incinerators

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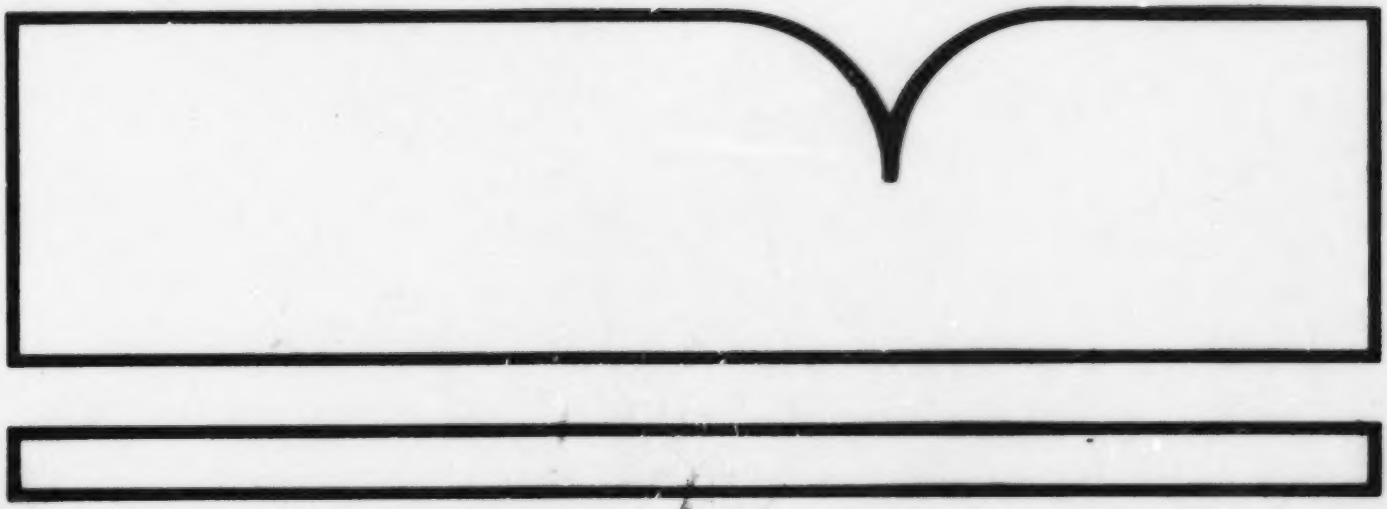

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16. ABSTRACT

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# Characterization of Particulate Emissions from Municipal Wastewater Sludge Incinerators

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■ Particulate emissions from a group of municipal sludge incinerators, three with multiple-hearth furnaces and one with a fluidized-bed furnace, were characterized. Three plants operated at or near autogenous burning conditions. Chemical element composition was determined for total and sized emission samples by X-ray fluorescence analysis. Objectives of the investigation were to obtain specific elemental emission factors and to provide source inventories and source signatures, especially in terms of particle size, to assist the development and evaluation of source apportionment models. Considerable enrichment of several elements (S, V, Cu, Zn, Cd, Sn, Pb) in the particulate emissions compared to their content in the sludge feed was observed. The largest average enrichment ratios were found with cadmium (31), zinc (13), lead (9), and sulfur (8).

## *Introduction*

With the trend in the production of municipal wastewater sludge on a definite increase, an attendant increase in the use of incineration in the management of sludge disposal is expected. A characterization study has been conducted on the particulate emissions from the stacks of a group of municipal sludge incinerators, three with multiple-hearth furnaces and one with a fluidized-bed furnace. One purpose of the investigation was to provide information on the concentration of chemical elements, especially heavy metals such as cadmium and lead, in the emissions. A related objective was to obtain source emission factors and source signatures to assist in the development and validation of source apportionment models.

The chemical compositions of municipal sludges vary with location and time because the sludges result from a diversity of manufacturing activities as well as human excreta and food residues. Thus, as demonstrated in the analyses of Furr et al. (*1*) on the municipal sludge from 16 cities, there is no typical sludge. Enrichment of some elements, notably Cd and Pb, in the emissions from incineration compared to the concentration in the sludge feed can occur. Therefore, predictions of the stack emissions based on the content of the sludge being burned are likely to be erroneous.

These investigations involved the collection of representative emission samples for particulate mass emission determination, for chemical characterization, and for particle size determinations of total mass emissions and individual chemical element emissions. Sulfur dioxide and sulfuric acid emissions were determined. The gaseous concentration of hydrocarbons and nitrogen oxides were monitored, and a few samples were collected to determine the emissions of high molecular weight organic compounds. At each plant process, samples of the feed sludge were collected and analyzed. Information on the four incinerator facilities during the test periods are shown in Table I.

The sludge was preconditioned thermally with the hot exhaust gases from the furnaces to produce a higher solids sludge cake for better burning. At the multiple-hearth incinerator O, this process was carried to the point of positive heat balance, autogenous burning. Some supplemental fuel was burned at all of the sites. At incinerator O only a total of 16 gal of fuel oil was burned, and that only during the last two of the 29-h sampling periods for shutdown purposes. The remainder of the time the sludge was autogenously combusted. At incinerator P an average of 40 $ft^3/h$ of natural gas was burned. The supplemental fuel oil at incinerator Q ranged from 0 to 64 gal/h and averaged 17 gal/h over the 3-day test period. Incinerator R was not designed for autogenous combustion and never reached this condition. An average of 40 gal/h of fuel oil was burned.

## *Experimental Section*

**Sampling Procedures.** A standard U.S. Environmental Protection Agency (EPA) Method 5 sampling train (*2*) was used to collect particulate samples for mass emission rate determinations. The impingers were adapted to determine gaseous sulfur oxides by EPA Method 8 (*3*). The first impinger contained 150 mL of 80% isopropanol and was followed by a high purity glass wool plug in the U-tube between the first and second impinger. The second and third impingers contained 100 mL each of 3% hydrogen peroxide solution and the fourth impinger was filled with approximately 400 g of indicating silica gel. Prior to sampling, a velocity profile of the duct at the sampling location was determined through transversing. All Method 5 and Method 8 samples were collected with a 5-ft heated Pyrex-lined probe at a single point having the average velocity of the flue gas within the duct.

Samples used for chemical characterization by X-ray fluorescence analysis (XRF) were collected with a modified Method 5 train in which the conventional sample box, filter holder, and glass impingers were replaced by an EPA-designed heated sample box that housed a stainless steel

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Table I. Furnace Types, Control Systems, and Sludge Loadings of Tested Incinerators

| site designation | furnace type | control equipment | av load of unit tested, kg/h (dry) | sludge moisture, % |
|---|---|---|---|---|
| O | seven-chambered multiple-hearth | wet, tray-type scrubber | 1940 | 63.5 |
| P | eight-chambered multiple-hearth | wet, tray-type scrubber | 1740 | 49.3 |
| Q | fluidized-bed | wet, tray-type scrubber | 839 | 66.2 |
| R | seven-chambered multiple-hearth | single-pass cyclone scrubber | 1890 | 71.3 |

Table II. Elemental Composition (%) of Municipal Wastewater Sludge

| element | site O | | site P | | site Q | | site R | | av content 16 cities[a] |
|---|---|---|---|---|---|---|---|---|---|
| | av | sd | av | sd | av | sd | av | sd | |
| Na | 1.0 | 0.09 | 0.7 | 0.11 | <0.6 | | <0.2 | | 0.44 |
| Mg | 1.8 | 0.08 | 1.0 | 0.17 | 0.87 | 0.13 | 0.92 | 0.03 | 0.60 |
| Al | 3.4 | 0.28 | 3.6 | 0.47 | 4.0 | 0.23 | 5.2 | 0.14 | 1.83 |
| Si | 10.1 | 0.46 | 13.0 | 3.3 | 17.0 | 2.7 | 12.0 | 0.34 | |
| P | 6.4 | 0.44 | 4.4 | 0.22 | 4.1 | 0.13 | 3.7 | 0.12 | 1.56 |
| S | 0.93 | 0.15 | 1.3 | 0.41 | 0.82 | 0.46 | 0.47 | 0.06 | |
| Cl | 0.45 | 0.01 | 0.08 | 0.18 | <0.5 | | 0.68 | 0.19 | 0.38 |
| K | 1.3 | 0.09 | 1.1 | 0.24 | 1.2 | 0.15 | 1.1 | 0.02 | 1.22 |
| Ca | 17.0 | 0.62 | 6.2 | 1.2 | 7.5 | 1.0 | 9.8 | 0.15 | 3.62 |
| Ti | 0.84 | 0.06 | 0.76 | 0.05 | 0.77 | 0.04 | 1.18 | 0.04 | 0.23 |
| V | 0.03 | 0.01 | 0.04 | 0.01 | 0.03 | 0.01 | <0.01 | | 0.004 |
| Cr | 0.22 | 0.02 | 0.50 | 0.27 | 0.22 | 0.24 | 0.38 | 0.02 | 0.14 |
| Mn | 0.70 | 0.11 | 0.23 | 0.11 | 0.34 | 0.12 | 0.11 | 0.008 | 0.019 |
| Fe | 6.7 | 1.0 | 17.0 | 7.9 | 7.6 | 6.4 | 5.4 | 0.10 | 3.06 |
| Co | 0.01 | 0.003 | 0.03 | 0.02 | 0.01 | 0.02 | 0.01 | 0.002 | 0.001 |
| Ni | 0.03 | 0.01 | 0.14 | 0.08 | 0.06 | 0.07 | 0.06 | 0.008 | |
| Cu | 0.12 | 0.02 | 0.75 | 0.43 | 0.27 | 0.37 | 0.44 | 0.02 | 0.13 |
| Zn | 0.30 | 0.04 | 1.1 | 0.08 | 1.0 | 0.07 | 1.4 | 0.03 | 0.21 |
| As | <0.3 | | <0.3 | | <0.03 | | <0.03 | | 0.0014 |
| Se | <0.04 | | <0.04 | | <0.04 | | <0.04 | | 0.0003 |
| Br | <0.05 | | <0.05 | | <0.05 | | <0.05 | | 0.005 |
| Cd | 0.02 | 0.005 | 0.04 | 0.05 | 0.08 | 0.04 | 0.03 | 0.005 | 0.010 |
| Sn | 0.30 | 0.02 | 0.25 | 0.03 | 0.25 | 0.03 | 0.19 | 0.006 | 0.022 |
| Sb | 0.03 | | 0.02 | 0.004 | 0.01 | 0.001 | 0.01 | 0.001 | 0.001 |
| Ba | 0.25 | 0.02 | 0.41 | 0.11 | 0.45 | 0.04 | 0.27 | 0.01 | 0.06 |
| Pb | 0.34 | 0.13 | 0.48 | 0.18 | 0.59 | 0.25 | 0.23 | 0.03 | 0.18 |

[a] Reference 1.

filter holder for 47-mm filters. The particulate characterization samples were collected in sets consisting of two Gelman A glass fiber filters and two Millipore AA, one Nuclepore 0.8 μm, and six Teflon 0.2 μm filters. Sampling periods ranged from 15 s to 10 min to provide a variety of loading on the filters. In all cases, an attempt was made to sample isokinetically. The Millipore and Teflon filters were analyzed by XRF.

University of Washington Mark III cascade impactors were used to collect samples for particle size distribution measurements of total mass and individual chemical element. The impactor samples were taken in-stack at the sampling point of average gas velocity used for the characterization sampling. Samples were collected isokinetically with a sampling rate between 0.5 and 0.75 $ft^3$/min through the impactor.

Composite preburn sludge samples and postburn ash were collected at all incinerators except the fluidized-bed unit, where only sludge samples were taken. The sludge samples were heated to 600 °C for 30 m to remove the volatile content before their chemical analysis.

Each site was monitored during the testing period on a continuous basis for nitrogen oxides and hydrocarbon emissions. A heated Teflon line was used to deliver the samples to a Thermo Electron Model 44 duel Chamber single detector monitor for nitrogen oxides and to a Scott Model 166 total hydrocarbon analyzer with a single ionization detector.

**Analytical Methods.** Elemental contents of the emission characterization, sludge, and ash samples were determined with a Siemens MRS-3 multichannel wavelength dispersive X-ray fluorescence spectrometer with 15 fixed-wavelength monochromators and a scanning channel to analyze for 11 additional elements. Requirements of this system, which has been optimized for the analysis of aerosol samples (*4*), are light, uniform deposits on low-mass substrates. The characterization samples collected on Teflon, Millipore, and Nuclepore filters were analyzed directly. Samples that were collected with the cascade impactors resulted in small piles on the impactor stages that could not be analyzed directly. The material on each stage was suspended in liquid and subsequently redeposited on polycarbonate films (poreless Nuclepore) (*5*). Bulk samples such as the ashed process feed sludge and the thick deposits on glass fiber filters were formed into thin carbowax films suitable for XRF analysis. The samples were ground, mixed with carbowax and solvent in an agate mortar and pestle until the solvent dried, and then transferred to a hydraulic press where a flat specimen was formed under 10 tons of force. Solutions such as those obtained from the backup impinger of Method 5 were analyzed by procedures recently developed in our laboratory (*6*). A Collision nebulizer was used to generate liquid aerosols from the analytic solution. Adequate dilution was added to dry the particles. A filter in the air stream after a small mixing chamber was used to collect thin, uniform deposits suitable for analysis.

## *Results and Discussion*

**Sludge Content.** The composition of the ashed sludge

Table III. Change of Elemental Composition (%) of Sludge from Incinerator O with Heating

| element | temp, °C | | | | | | normalized enrichment[a] |
|---|---|---|---|---|---|---|---|
| | 100 | 200 | 400 | 600 | 800 | 1000 | |
| Mg | 0.53 | 0.60 | 1.5 | 1.6 | 1.8 | 1.9 | 0.98 |
| Al | 0.86 | 0.86 | 2.4 | 2.4 | 2.8 | 2.9 | 0.89 |
| Si | 2.5 | 2.4 | 7.7 | 7.4 | 8.8 | 9.2 | 0.94 |
| P | 1.6 | 1.6 | 4.5 | 4.5 | 4.9 | 5.3 | 0.89 |
| S | 0.54 | 0.59 | 0.88 | 0.86 | 0.91 | 0.64 | 0.50 |
| K | 0.33 | 0.32 | 1.0 | 1.0 | 1.1 | 1.2 | 1.00 |
| Ca | 4.1 | 4.1 | 12.6 | 12.2 | 13.7 | 14.8 | 0.93 |
| Ti | 0.21 | 0.19 | 0.60 | 0.60 | 0.64 | 0.68 | 0.91 |
| Cr | 0.07 | 0.11 | 0.23 | 0.23 | 0.24 | 0.20 | 1.04 |
| Mn | 0.22 | 0.18 | 0.60 | 0.58 | 0.66 | 0.66 | 0.84 |
| Fe | 1.9 | 1.8 | 6.1 | 6.4 | 6.7 | 7.2 | 1.07 |
| Co | | | | 0.01 | 0.01 | 0.01 | |
| Ni | | | 0.03 | 0.04 | 0.04 | 0.04 | |
| Cu | 0.04 | | 0.11 | 0.13 | 0.13 | 0.13 | 1.09 |
| Zn | 0.09 | 0.08 | 0.29 | 0.31 | 0.33 | 0.32 | 0.97 |
| Cd | | | 0.01 | 0.02 | 0.02 | 0.02 | |
| Sn | 0.09 | 0.09 | 0.24 | 0.24 | 0.28 | 0.27 | 0.85 |
| Ba | 0.06 | 0.05 | 0.19 | 0.18 | 0.21 | 0.20 | 0.95 |
| Pb | | | 0.24 | 0.24 | 0.29 | 0.15 | |

[a] Enrichment at 600 °C relative to potassium (% element/% potassium) at 600 °C divided by (% element/% potassium) at 100 °C.

feed material is shown in Table II for the elements determined by XRF. The values are the averages for four to six composite samples taken during the 2–3-day testing periods at each incinerator. The relative standard deviation was generally less than 10% for the more abundant elements (concentration greater than 1%). For comparison, the average content of sludge from 16 cities as determined by Furr et al. (*1*) is also listed in Table II. To determine whether there were significant volatilization losses of the analyzed elements during the ashing of sludge samples at 600 °C, we heated a group of samples for 45 min at the temperatures indicated in Table III and analyzed them by XRF. The concentration of each element at 600 °C was compared to its concentration in the unwashed (100 °C dried) sludge sample. The concentrations were normalized to that of a nonvolatile element (potassium) at the two temperatures. The results from samples taken at incinerator O, shown in the last column of Table III, indicate that only sulfur was significantly changed relative to potassium. Similar results were found with samples from incinerator P.

The nonvolatile elemental content of the postburn bottom ash samples from the three multiple-hearth furnaces was essentially the same as found in ashed sludge samples from those sites. No bottom ash was available at the fluidized-bed incinerator as the ash, which was less dense than the sand of the bed, was continuously swept out at the top of the reactor. Greenberg et al. (*7*) have recently reported an investigation on another fluidized-bed incinerator in which they examined the composition of the ash collected at the bottom of the scrubber. For most elements, they found a ratio of concentration in the scrubber bottom ash to concentration in sludge of less than 1.0. This was attributed to loss by vaporizing out of the sludge or dissolving in the scrubber solution.

**Elemental Emissions.** The mean concentrations of the elements determined by XRF in the emissions from the four plants are shown in Table IV. The relative standard deviation of the samples analyzed (between 45 and 95 samples per site) to obtain each of these concentrations averaged 33%, 72%, 32%, and 68% for O, P, Q, and R, respectively. The greater variability of P and R reflect the wider range of operating conditions, i.e., the rates of feed and stack gas flow during the testing periods. It is immediately apparent that some of the elements such as zinc, cadmium, and lead were higher in the emissions than would have been expected based solely on their concentration in the sludge. Table V lists the average composition of the emission sample from each incinerator in per cent of the total mass. The concentrations of lead in the emissions have increased to about 3% from a mean concentration of 0.5% in the sludges. Enrichment factors, calculated by dividing the concentration in the sludge, are listed in Table VI. Conditions causing enrichment are volatility and association of the volatile elements with the extremely fine particles that are not efficiently removed by scrubbers.

**Total Particulate Mass and Sulfur Oxides.** The emission rates and concentrations of particulate mass, sulfur dioxide, and sulfuric acid were obtained from the Method 5 and Method 8 tests run after the scrubber outlets. The emissions shown in Table VII are the mean values obtained from running six to eight tests at each incinerator. Lowest particulate emissions were observed at the fluidized-bed incinerator, Q. The higher sulfur oxide emissions from incinerator R were presumably attributable to the supplementary fuel oil that was burned to maintain combustion.

**Nitrogen Oxides and Hydrocarbons.** The results of monitoring oxides of nitrogen and total hydrocarbons are shown in Table VIII. The sample values are 20-min averages of strip chart recordings; the averages represent the mean of all the 20-min averages. The average concentrations are similar at incinerator O, P, and Q, but the nitrogen oxides are much lower at R. No measurement of hydrocarbons was made at R.

**Particle Size Distribution.** The average mass median diameters obtained from the particle size distribution measurements were 0.28, 0.30, 1.1, and 0.85 μm at incinerators O, P, Q, and R, respectively. Individual size distributions for several elements as well as the total mass distribution are shown on Figure 1. For convenience, the largest and smallest size fractions have been assigned finite values. The zinc distribution (1A), predominantly submicrometer particles, was characteristic of the sulfur, cadmium, lead, and other elements which exhibited enrichment in the emission probably because of their volatility in the furnace. Phosphorus (1B) exhibited a group of midrange particles around 2 μm. Iron was distributed through all sizes with a significant fraction of large particles

Table IV. Mean Concentrations of Elemental Emission ($\mu g/m^3$)[a] from Municipal Sludge Incinerators

| element | site O | | site P | | site Q | | site R | |
|---|---|---|---|---|---|---|---|---|
| | av | sd | av | sd | av | sd | av | sd |
| Na | 350 | 110 | 290 | 230 | 100 | 50 | 240 | 170 |
| Mg | 90 | 32 | 440 | 550 | 51 | 18 | 21 | 6 |
| Al | 128 | 47 | 1570 | 1980 | 160 | 48 | 37 | 20 |
| Si | 590 | 100 | 4180 | 4826 | 270 | 80 | 620 | 290 |
| P | 590 | 120 | 1730 | 1890 | 210 | 69 | 570 | 350 |
| S | 660 | 300 | 930 | 410 | 730 | 270 | 2610 | 910 |
| Cl | 230 | 90 | 130 | 110 | 47 | 65 | 1990 | 2280 |
| K | 210 | 90 | 460 | 500 | 54 | 22 | 120 | 110 |
| Ca | 780 | 170 | 2620 | 2660 | 440 | 150 | 160 | 88 |
| Ti | 28 | 12 | 450 | 460 | 33 | 10 | 16 | 21 |
| V | ~35 | | 38 | 14 | 9 | 2 | <6 | |
| Cr | 97 | 39 | 480 | 330 | 14 | 8 | 230 | 106 |
| Mn | 27 | 13 | 82 | 30 | 23 | 8 | 10 | 1 |
| Fe | 370 | 80 | 7070 | 8170 | 228 | 71 | 230 | 145 |
| Co | <6 | | 25 | 8 | <6 | | <6 | |
| Ni | <22 | | 125 | 121 | <22 | | <22 | |
| Cu | 85 | 29 | 810 | 690 | 14 | 4 | 520 | 310 |
| Zn | 810 | 220 | 1840 | 1240 | 87 | 28 | 1830 | 1650 |
| As | <29 | | <29 | | <29 | | <29 | |
| Se | ~45 | | 20 | 3 | 18 | 17 | 26 | 1 |
| Br | ~49 | | 57 | 19 | 39 | 17 | 170 | 140 |
| Cd | 42 | 15 | 34 | 15 | 7 | 2 | 1890 | 1410 |
| Sn | 180 | 51 | 1230 | 450 | 30 | 9 | 790 | 640 |
| Sb | 6 | 2 | 23 | 7 | <2 | | 43 | 40 |
| Ba | 10 | 4 | 290 | 280 | 20 | 7 | 14 | 15 |
| Pb | 510 | 190 | 1170 | 530 | 114 | 65 | 2140 | 1880 |

[a] Corrected to normal temperature and pressure (20 °C, 1 atm).

Table V. Mean Composition (% of Total Mass) of Elements in Particulate Emissions from Municipal Sludge Incinerators

| element | site | | | |
|---|---|---|---|---|
| | O | P | Q | R |
| Na | 2.76 | 0.57 | 1.96 | 0.34 |
| Mg | 0.71 | 0.86 | 1.01 | 0.03 |
| Al | 1.02 | 3.05 | 3.07 | 0.05 |
| Si | 4.69 | 8.13 | 5.33 | 0.91 |
| P | 4.69 | 3.36 | 4.14 | 0.84 |
| S | 5.25 | 1.80 | 14.42 | 3.83 |
| Cl | 1.80 | 0.26 | 0.93 | 2.91 |
| K | 1.71 | 0.89 | 1.07 | 0.18 |
| Ca | 6.20 | 5.09 | 8.76 | 0.23 |
| Ti | 0.22 | 0.88 | 0.65 | 0.02 |
| V | 0.28 | 0.07 | 0.18 | |
| Cr | 0.77 | 0.94 | 0.28 | 0.33 |
| Mn | 0.21 | 0.16 | 0.46 | 0.01 |
| Fe | 2.91 | 13.75 | 4.52 | 0.34 |
| Co | | 0.05 | | |
| Ni | | 0.24 | | |
| Cu | | 1.58 | 0.28 | 0.77 |
| Zn | 6.44 | 3.58 | 1.72 | 2.69 |
| Se | | 0.04 | 0.36 | 0.04 |
| Br | | 0.11 | 0.77 | 0.26 |
| Cd | 0.33 | 0.07 | 0.13 | 2.77 |
| Sn | 1.42 | 2.39 | 0.59 | 1.16 |
| Sb | 0.05 | 0.05 | | 0.06 |
| Ba | 0.08 | 0.56 | 0.40 | 0.02 |
| Pb | 4.07 | 2.27 | 2.26 | 3.14 |

Table VI. Enrichment Ratios of Elements in Emissions Relative to Content in Sludge

| element | incinerator | | | | av enrichment |
|---|---|---|---|---|---|
| | O | P | Q | R | |
| Na | 2.76 | 0.81 | | | |
| Mg | 0.42 | 0.86 | 1.16 | 0.03 | 0.38 |
| Al | 0.30 | 0.85 | 0.78 | 0.01 | 0.49 |
| Si | 0.46 | 0.63 | 0.31 | 0.08 | 0.37 |
| P | 0.73 | 0.76 | 1.01 | 0.23 | 0.68 |
| S | 5.64 | 1.38 | 17.6 | 8.14 | 8.19 |
| Cl | 4.00 | 0.63 | | 4.28 | 2.97 |
| K | 1.32 | 0.81 | 0.89 | 0.16 | 0.80 |
| Ca | 0.36 | 0.82 | 1.16 | 0.023 | 0.59 |
| Ti | 0.26 | 1.16 | 0.84 | 0.02 | 0.62 |
| V | 9.33 | 1.75 | 6.0 | | 5.69 |
| Cr | 3.50 | 1.88 | 1.27 | 0.87 | 1.88 |
| Mn | 0.30 | 0.70 | 1.35 | 0.10 | 0.61 |
| Fe | 0.43 | 0.81 | 0.59 | 0.06 | 0.54 |
| Co | | 1.67 | | | |
| Ni | | 1.71 | | | |
| Cu | 5.67 | 2.11 | 7.0 | 1.75 | 4.13 |
| Zn | 21.47 | 3.25 | 28.7 | 1.89 | 13.83 |
| Br | | | 7.7 | | |
| Cd | 16.50 | 7.0 | 1.6 | 98.9 | 31. |
| Sn | 4.73 | 9.56 | 2.36 | 6.10 | 5.68 |
| Sb | 1.67 | 2.50 | | 4.6 | 2.92 |
| Ba | 0.32 | 1.36 | 0.89 | 0.07 | 0.66 |
| Pb | 11.97 | 4.70 | 3.83 | 13.65 | 8.53 |

evident even in the controlled (post scrubber) emissions. Only a very small fraction of the total mass (1D) was greater than 2 $\mu$m.

At incinerator R particle size measurements were also made before the scrubber. Figure 2 shows the distribution at the scrubber inlet (2C) where large particles were preponderant, but a second mode occurred near 2 $\mu$m and at the scrubber outlet (2D), where the mass concentration of the smaller particles predominated because of more efficient removal of the larger particles by the scrubber. The

Table VII. Emission Rates and Concentrations of Total Particulate Mass and Sulfur Oxide Gases

| incinerator | particulate mass | | $SO_2$ | | $H_2SO_4$ | |
|---|---|---|---|---|---|---|
| | kg/h | mg/m³ | kg/h | ppm | kg/h | ppm |
| O | 0.89 | 13.7 | 0.07 | 0.4 | 0.10 | 0.4 |
| P | 2.98 | 103.2 | 0.16 | 2.1 | 0.15 | 1.3 |
| Q | 0.094 | 9.4 | 0.30 | 11.1 | 0.022 | 0.6 |
| R | 2.13 | 199.6 | 3.34 | 92.4 | 0.31 | 7.0 |

[a] Concentrations corrected to normal temperature and pressure (20 °C, 1 atm).

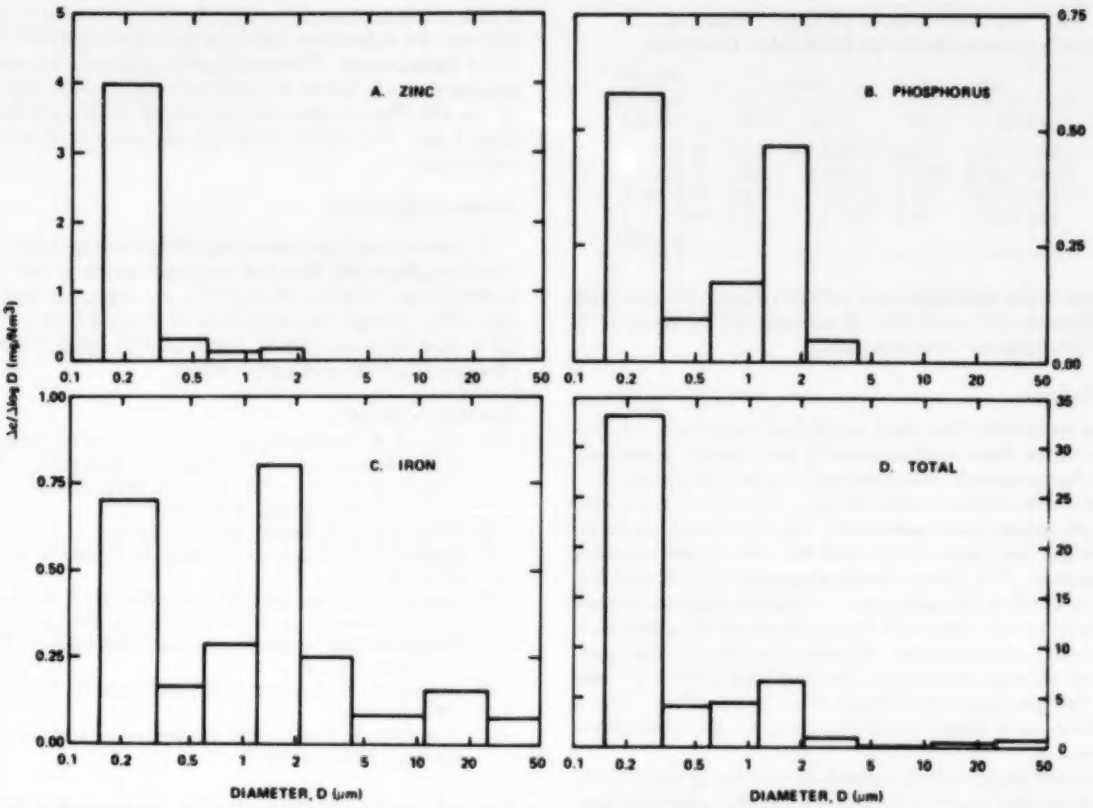


**Figure 1.** Particle size distribution of zinc, phosphorus, iron, and total particulate emissions from incinerator O.

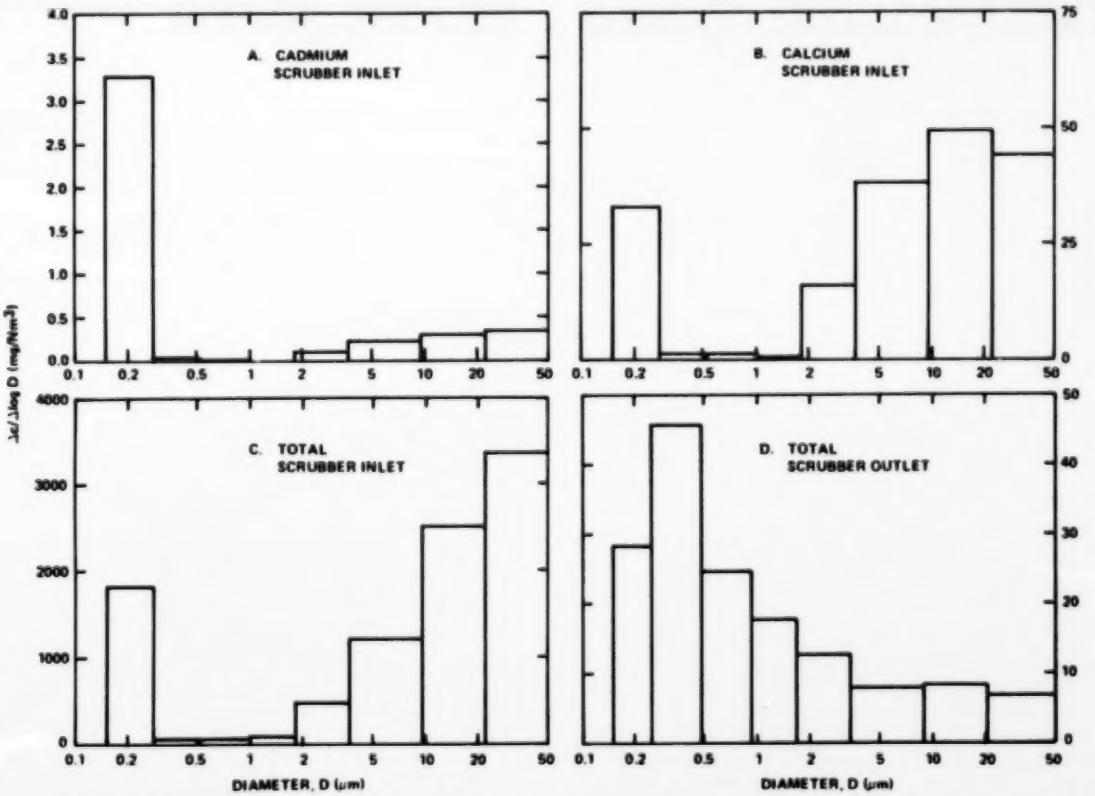


**Figure 2.** Particle size distribution of cadmium, calcium, and total particulate mass before the scrubber and total particulate emission after the scrubber at incinerator R.

Table VIII. Concentration of Nitrogen Oxide and Hydrocarbon (ppm) in Sludge Incinerator Emissions

| incinerator | NO | | $NO_2$ | | hydrocarbons, |
|---|---|---|---|---|---|
| | range | av | range | av | range |
| O | 8.8-105.8 | 31.4 | 3.2-61.3 | 22.7 | 6-7.2 |
| P | 18.9-139.9 | 102.5 | 0-63.5 | 26.2 | 3-6.4 |
| Q | 15.1-153.6 | 75.2 | 0-74.5 | 33.5 | 6.2-11.1 |
| R | 3.0-16.5 | 9.7 | 0-4.7 | 2.2 | not monitored |

contrast in the distribution of a more volatile element such as cadmium (2A) with that of calcium (2B) is evident in these prescrubber measurements.

## *Conclusions*

The emissions from four municipal wastewater sludge incinerators, three multiple-hearth and one fluidized-bed, were characterized. The total particulate emissions, particle size distribution, sulfur oxides, elemental content, and nitrogen oxides were measured. The elemental composition of the feed stock sludge and the bottom ash was also determined. The more volatile elements, Cd, Pb, and Zn, were enriched in the emissions. Cd had the highest average enrichment ratio with a 31-fold increase in the emissions. The average mass median diameters for the emitted particles at all sites were small, ranging from 0.28 to 1.1 μm. Very few particles were larger than 2 μm. The volatile elements were found predominantly in the submicron particles.

The enrichment of Cd (especially relative to that of Zn) is much greater at incinerator R than at the other facilities. A contributing factor to this higher enrichment is the greater predominance of Cd in small particles and the lower efficiency of the control device. Incinerator R has a wet, single-pass scrubber system that is considerably less efficient for submicron particles than the scrubbers at the other incinerators. Elemental particle size measurements at incinerator R before the scrubber inlet showed that 72% of the Cd (Figure 2A) was associated with particles less than 1 μm. Only 28% of the Zn was associated with this size range.

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